THE ROLE OF HETERODYNE DETECTION IN FUTURE SPACE MISSIONS

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ABSTRACT

The utility of heterodyne detection in future space mission applications is discussed. Cases where heterodyne techniques are preferred to direct detection almost always involve the need for high spectral resolution. However, this is more common than might be thought, because the future large telescopes or interferometers in space may have very high spatial resolution, which implies relatively small velocity dispersion and therefore high spectral resolution. The case of a large ALMA-like interferometer in space is briefly discussed.

INTRODUCTION

It is often not immediately obvious which detection technique, heterodyne or direct, will be superior for a given science goal. Particular cases have been analyzed and general rules established (e.g., Phillips, 1988 ; Zmuidzinas, 2002). The answer is dependent on several factors, including the frequency of observation, the background emission strength and the spectral resolution needed. There are both fundamental and practical differences in the two techniques and they may have to be considered carefully. Fundamentally, heterodyne detection, or any process involving the use of an amplifier at the received signal frequency, is limited by quantum noise, whereas direct detection, e.g., by a bolometer or photodetector, is limited by the background intensity seen by the detector. Quantum noise increases linearly with frequency, but direct detection has no contribution from quantum noise. Therefore, in general, heterodyne detection is more useful at long wavelengths, and direct detection at shorter wavelengths. Actually, in the case that the background emission is dominant for both direct and heterodyne, the two devices have the same sensitivity, other things being equal (Phillips, 1988).

The resolution required is a critical parameter. Although neither device has a fundamental resolution limit, the radio (heterodyne or amplifier) technique can easily accommodate resolutions of 10^7, but, in the submillimeter band, direct detection techniques are usually limited to resolution of a few thousand.

An examination of the situation in astrophysics for the case of line studies leads to the conclusion that, the better the spatial resolution, the better the spectral resolution requirement. So, while it may be that direct detection is the correct technique in many cases, ultimately, to get the most information from very large telescopes and interferometric arrays, heterodyne devices will be needed. Even relatively small telescopes, by modern standards (~ 10m), at a wavelength of ~ 1mm, run into this problem. As an example, the relatively nearby galaxy, CenA, has spectral features in CO observations of about 10 km/s, which means that a resolution of ~ 10^5 is needed.

There are many advantages to space telescopes, but the obviously dominant reason for paying the high price of a space platform is the lack of atmosphere. Figure 1. shows the transmission in the submillimeter band for Mauna Kea (upper) and SOFIA (lower). Not only will the absorption of the Earth's atmosphere be avoided, but the very significant emission, even for SOFIA, will be eliminated, leading to greatly improved detector performance.

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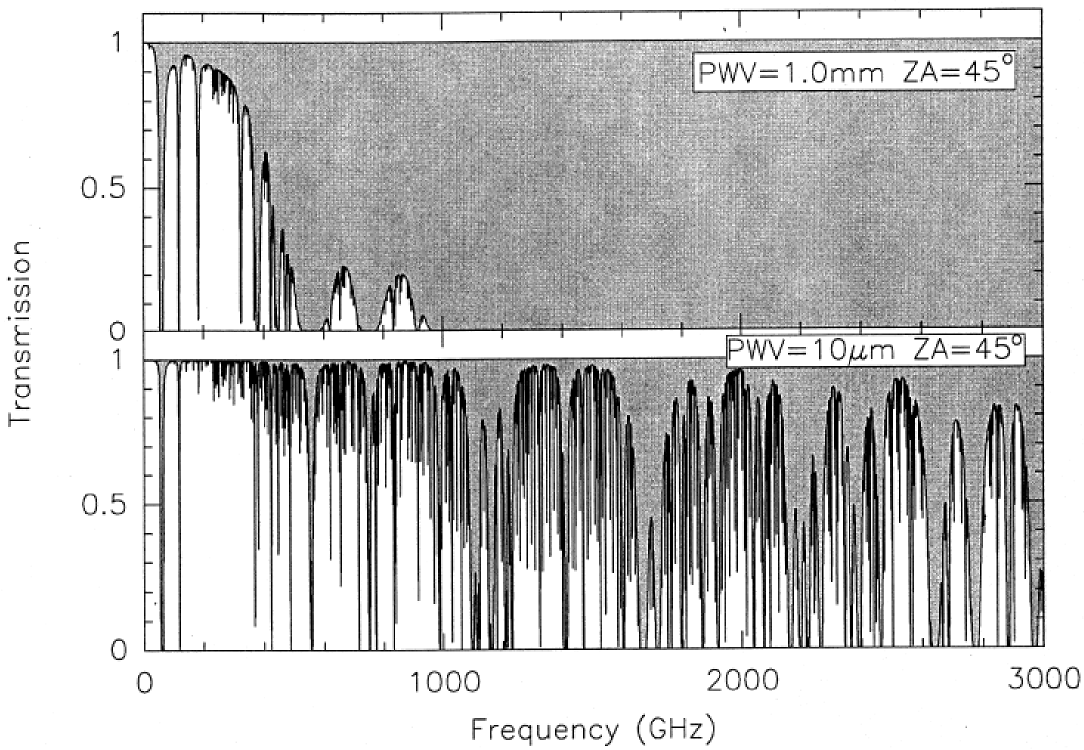

Figure 1 *The spectrum of the transmission of the Earth's atmosphere, from Mauna Kea (upper) and from SOFIA (lower).*

THE DENSE ISM

Line-Surveys

Investigations of the physics and chemistry of the ISM, whether by means of a large single dish in space, or a multielement interferometer, need velocity resolution of better than 0.1 km/s, or $3x10^6$. An observing technique, known as a line-survey (e.g., Blake et al. 1986), has become a popular method for gaining an overview of the chemical state of a molecular or circumstellar cloud. A ground-based example, a line-survey for Orion-IRC2, is shown in Figure 2. The confusion limit, where neighboring lines overlap, has been reached. Although a survey such as this represents a large effort for a ground-based observatory (Schilke et al. 2001), HIFI on Herschel will be able to make a complete scan (more than a THz) of a GMC in a day, so providing a chemical analysis tool. This will be complete in the sense that all frequencies and therefore all chemical species will be available for analysis, including water and the many species hidden under the atmospheric water lines.

A similar study can sometimes be carried out for comets, and these experiments have suggested that the material of the comet is similar to that of the ISM (Lis et al. 1997).

Another aspect of the high resolution line-survey is that it measures the total flux carried by the lines (Groesbeck 1995; Sutton et al 1984). This can be compared with the total flux, continuum plus lines, as measured by a bolometric technique. While it might be surmised that the line contribution is negligible, this is certainly not true for the GMCs or the AGB star envelopes. Table 1 gives the line contribution for a few objects, showing values in the 10 – 60% range, for the 300 – 360 GHz band. A fast scanning, high resolution spectrometer on a space platform would be able to establish the situation over the full R-J band for many objects. This would assist the understanding of the apparently complex behavior of the dust emissivity parameter, β.

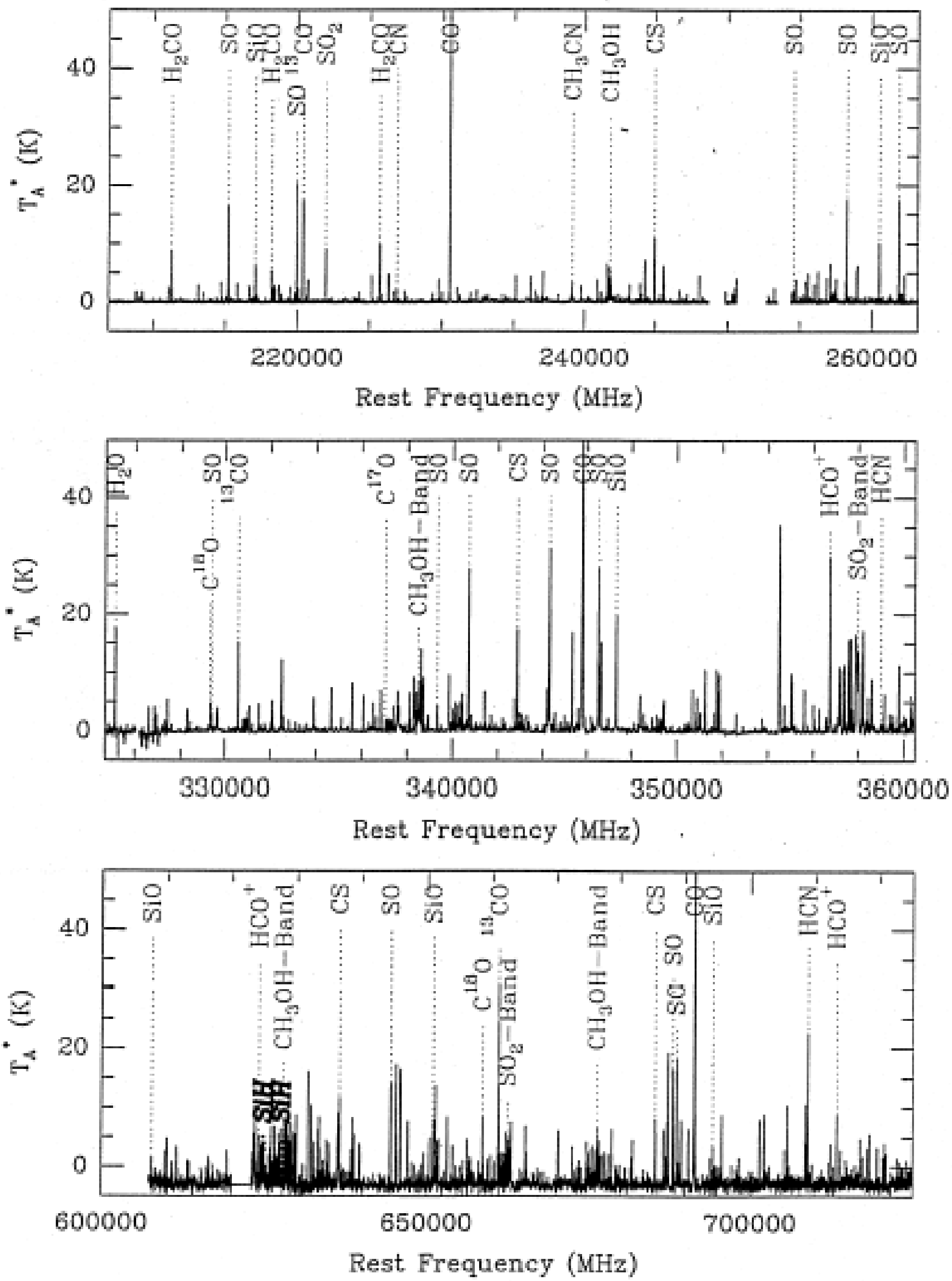

Figure 2 *A line-survey for Orion IRC2.*

SUMMARY OF LINE SURVEY FLUX RESULTS

Source	Frequency Range (GHz)	Coverage Achieved [a] (%)	Line Flux [b] (Jy)	Total Flux [c] (Jy)	Contribution of Line Flux (%)	Emissivity Index β [d]
Orion-KL	325–360	100	85	171 [e]	50	2.0 [f]
Orion-S	330–360	63	5.7	74 [e]	8	2.0 [f]
IRAS 16293–2422	330–360	50	0.9	17	5	1.0 [g]
IRC +10216	330–358	100	4.6	7.0 [h]	65	1.4 [i]
VY CMa	330–360	30	0.6	2.2	27	1.0 - 1.5 [j]
OH 231.8+4.2	330–360	30	0.5	2.2	23	1.0 - 1.5 [j]

Table 1 *The line contribution to the bolometric flux, for a variety of sources (Groesbeck, 1995).*

Important future ISM spectroscopic goals

There are large numbers of chemical species and spectral lines which are inaccessible from the ground, because they are too near H_2O lines or at too high a frequency. Probably the most important is H_2O, itself. Herschel and SOFIA will find many H_2O lines and a variety of hydride species. Which of these needs to be investigated further in more powerful future missions will be argued at the relevant time. An example is the HF molecule, which has the fundamental transition at about 1200 GHz. HF was detected by ISO (Neufeld et al. 1997), but because the spectrometer could not resolve the line, the S/N was poor and information limited. An estimate of the strength of a HIFI/Herschel detection is shown in Figure 3., together with the ISO detection. Clearly a strong signal results, which can be followed over wide ranges in the ISM.

SWAS has shown the ubiquity and complexity of the H_2O spectra, (an example is given in Figure 4.) but is limited to one line and much lower sensitivity (~ 1000) than HIFI/Herschel. With the complete set of lines (many 10s) available, future missions will be able to follow water in the full range of ISM situations, e.g., high density disks in star-formation.

A further example of high resolution requirements is given by the CI and CII fine-structure lines. In PDRs the 12CI and 13CI lines have been detected (Figure 5.) by Keene et al. (1998), but the line ratio is so large that moderate resolution (10^3) would cause the tail of the 12CI line to engulf the 13 CI line. A very important future measurement will be the 12CII/13CII ratio, as a function of galactic radius. This will give the most accurate 12C/13C ratio, because C+ is the dominant carbon species in the outer PDRs and diffuse clouds. It can only be done with high spectral resolution, however.

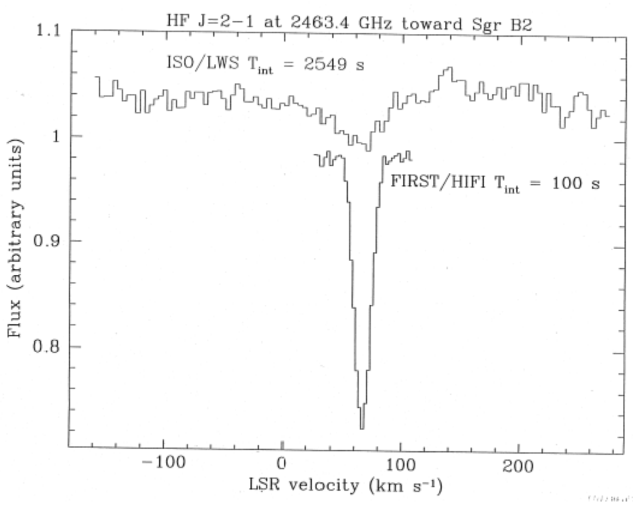

Figure 3 *The ISO detection of HF, together with an estimate for HIFI/ Herschel. For many sources the high resolution of HIFI will be even more effective than for the relatively wide-line source SgrB2, seen here.*

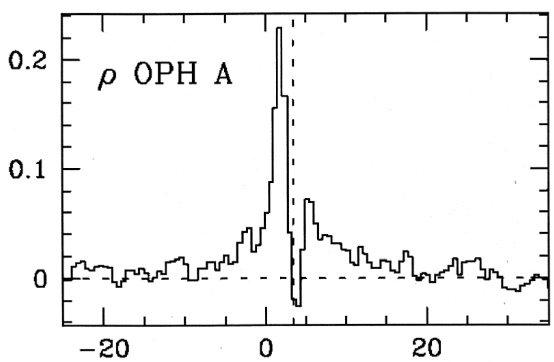

Figure 4 (above) *A SWAS detection of water in a Star-Forming region (Ashby et al. 1999).*

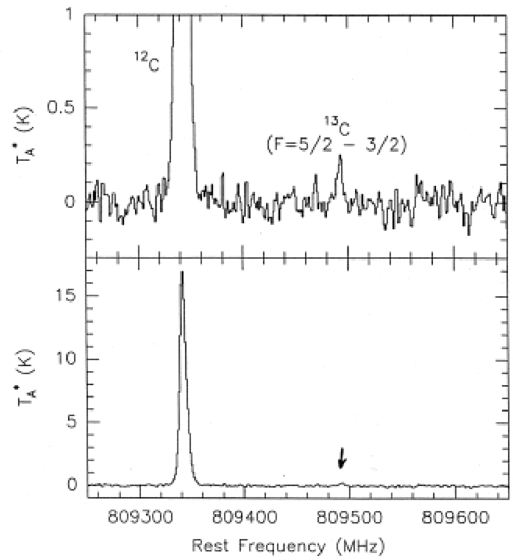

Figure 5 (right) *The detection of 13CI in a narrow-line PDR – the Orion Bar.*

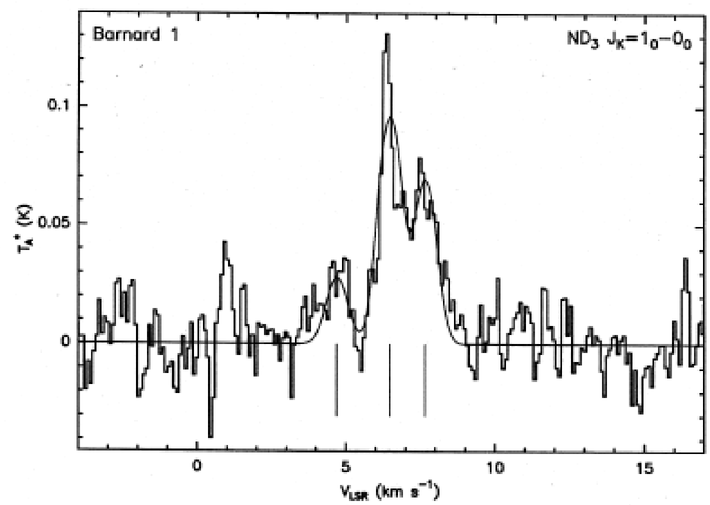

Figure 6 *The spectrum of triply deuterated Ammonia in B1. The identification is from the agreement with the lab frequency and the hyperfine structure.*

The biggest changes in isotopic substitution occur when D replaces H. At first sight it seems unlikely that deuteration would be observable, because H/D ~ 10^5. Nevertheless, species such as DCN and DCO+ have been observed and the deuteration found to be in the 10^{-1} to 10^{-3} range, depending on the physical situation. To quite general amazement, the fully deuterated ammonia molecule has been detected (Figure 6. , Lis et al, 2002; van der Tak et al, 2002). It is found in large column-density regions, where the cold gas has suffered chemical fractionation to a very high degree. Probably, the highly deuterated species condense on the grain mantles, together with most other molecules, until some perturbing process, such as an outflow from a young star, causes a shock-wave which removes the molecules from the mantles.

One ramification of these observations is the possibility that there may be a large reservoir of deuterated species in the very cold regions, but the molecules are unobservable due to their frozen state on the dust mantles. Given the importance of the H/D ratio it is interesting to try to determine whether HD, the assumed molecular-phase reservoir of D, has been depleted by the long term fractionation in the cold regions, together with turbulent mixing of dense and diffuse gas.

The ISM in External Galaxies

With current telescopes we are used to the appearance of galaxy spectra which have detail only for velocity dispersions of tens of km/s or greater. This will not be the case for high spatial resolution instrumentation. It has already been mentioned that the outer parts of the dust lane of CenA have an observed characteristic dispersion of about 10 km/s, even when observed with a 30" beam. We can get an idea of what the future higher resolution instrument will show by looking at absorption against the nucleus. In that case, the line-width is governed by the line-of-sight dispersion, as it will be for a small telescope beam. Figure 7. shows a variety of absorption features with structure down to a few km/s.

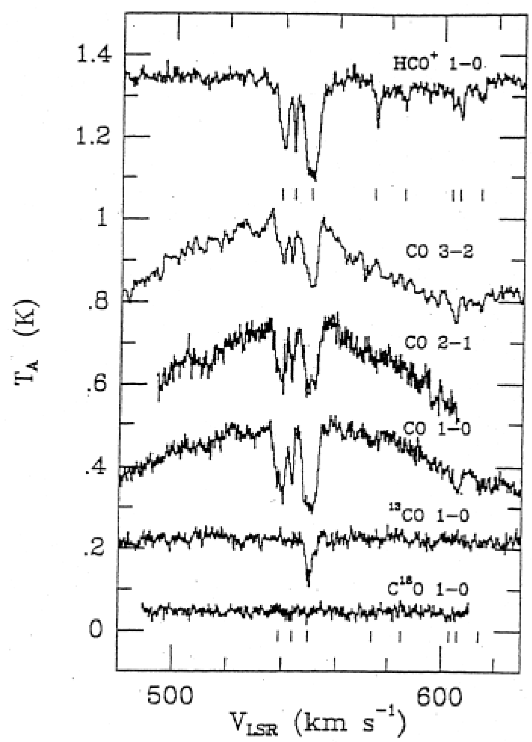

Figure 7 *Molecular absorption features against the nucleus of CenA (Israel et al. 1991).*

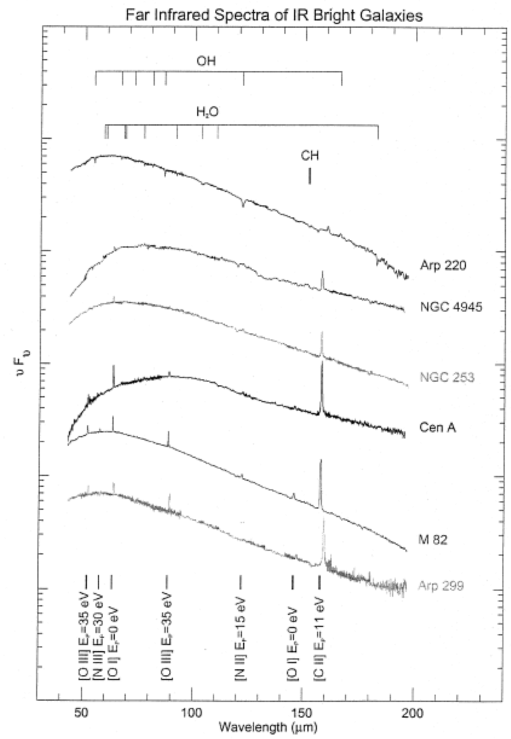

Figure 8 *ISO galaxy spectra.(Fischer, 2001).*

ISO spectra of bright galaxies are low resolution, because they are taken using a grating spectrometer. Examples are shown in Figure 8. Lines are clearly seen, but only the line-integral gives information. With high spectral resolution the line/continuum ratio would be much greater, the velocity structure would be revealed and, for cases such as Arp 220, the important CII (157 micron) line would be clearly seen and the resulting information on the line structure could be used to determine why the line is so weak. For instance, if the line were self-absorbed, this would be revealed by the lineshape.

Submillimeter Space Interferometers

The ultimate submillimeter device is presumably a giant interferometer in space, which we assume to be ALMA–like, for discussion purposes. For relatively small interferometers, with only a few telescopes, the argument concerning quantum noise vs background noise tells us that the direct detection technique would be superior. For ALMA in space, the relation between high spatial resolution and high spectral resolution almost certainly forces the use of heterodyne techniques, unless the instrument is designed only for continuum science.

However, there is another question concerning sensitivity. This is the issue of whether the direct detector interferometer, with N telescopes, is limited by the need to divide each telescope signal by N-1 to accomplish the beam combining. If so, for large N, the heterodyne interferometer is preferred.

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